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THE JOINT NOL/RAE/WRE RESEARCH PROGRAM ON BOMB DYNAMICS. PART II A LOW-DRAG BOMB WITH SPLIT-SKIRT STABILIZERS

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31 December 1969

NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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ATTENTION

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PART II A LOW-DRAG BOMB WITH SPLIT-SKIRT STABILIZERS

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ABSTRACT: Research on the free-fall dynamics of bombs has been conducted as a cooperative program supported by organizations in the United States, United Kingdom and Australia. In addition to full-scale flight trials of instrumented research stores carried out by the Australian Weapons Research Establishment (WRE), wind-tunnel tests have been made on mutually agreed models at the Aircraft Research Association and Royal Aircraft Establishment (RAE) in England; the Naval Ordnance Laboratory (NOL) in the United States; and at the Aeronautical Research Laboratory in Australia. RAE, WRE and NOL have separately prepared digital-computer programs to simulate test vehicle trajectories using wind-tunnel measurements as inputs. Correlation between the predicted and observed flight results have provided considerable insight into problems associated with dynamic behavior during the critical release phase and stability criteria needed for good ballistics consistency.

This is the second report on the research program and it presents results relating to the study of split-skirt stabilizers. These stabilizers are designed to eliminate the effects of roll-yaw cross coupling and to provide a variable-drag capability. Mechanical feasibility of an automatically opening two-position split-skirt stabilizer is examined. This report is being issued simultaneously by the Naval Ordnance Laboratory, the Royal Aircraft Establishment and the Weapons Research Establishment.

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THE JOINT NOL/RAE/WRE RESEARCH PROGRAM ON BOMB DYNAMICS

PART II A LOW-DRAG BOMB WITH SPLIT-SKIRT STABILIZERS

The purpose of this report is to summarize the tripartite cooperative free-fall research effort among NOL, WRE and RAE. A study was made of the characteristics of the split-skirt stabilizer using wind tunnels, digital-computer trajectory programs and instrumented free-fall weapons. This report is also being issued by the Royal Aircraft Establishment as RAE Technical Report 70038.

GEORGE G. BALL
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L. H. Schindel

L. H. SCHINDEL
By direction

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INTRODUCTION

A general investigation of the stability problems of freely falling missiles has been made in a joint United Kingdom/Australian research program which was initiated in 1960 and incorporated a series of free-flight trials of full-scale instrumented test vehicles, subsonic and transonic wind-tunnel tests and mathematical model studies using a digital computer (Ref. (1)). Correlations between predicted motions of the vehicle and behavior actually observed in the trials confirmed both the formulation of the mathematical model and the validity of wind-tunnel measurements. The results have provided considerable insight into problems associated with the release disturbance of bombs as they leave an aircraft and stability requirements needed for good ballistics consistency. Following technical discussion between representatives of the two countries and United States research establishments, the aims of the program were extended, and since 1964 it has been actively pursued on a tripartite cooperative basis. One notable feature of the enlarged program has been the attention given to testing novel stabilizing devices, such as split skirts and freely spinning tails (Ref. (2)).

A desirable feature of any weapon system lies in its adaptability to meet wide extremes in mission requirements. This is certainly true of an aircraft launched free-fall weapon. A weapon of this type may take varying forms dependent upon target characteristics. Nevertheless, tactical requirements may dictate widely varying delivery modes of the same weapon. Clearly, a high-altitude delivery would have quite different weapon trajectory requirements from a low-level release. The single aerodynamic characteristic of a bomb which most influences its performance is its drag. For release from high altitude, a bomb having low sensitivity to wind effects is of prime importance and this will be achieved using a low-drag shape. At the opposite extreme, delivery near ground level requires a bomb of high drag to avoid destruction of the launching aircraft. A variable-drag bomb would thus meet a wide variety of mission requirements. The split-skirt stabilizer is a proposed method of bomb stabilization to provide this variable-drag capability. A split-skirt stabilizer is formed by slicing a cylinder axially into petals, usually four in number, as indicated in Figure 1. Drag variation is accomplished by setting the petals of these skirts to different openings. Other aerodynamic advantages of this type of stabilizer were expected to be:

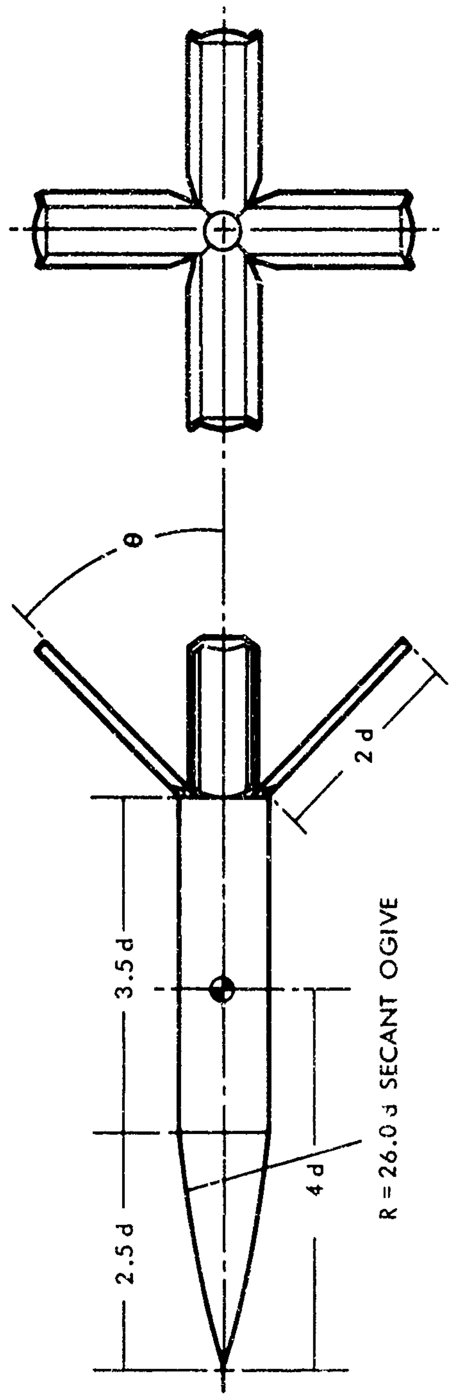


FIG. 1 SPLIT-SKIRT CONFIGURATION WITH N_1 NOSE

1. the characteristic yaw-induced rolling moments of the cruciform tail which contribute to the roll-yaw lock-in phenomena are avoided,

2. good static stability,

3. enhanced pitch damping,

4. improved aircraft installation and separation characteristics.

Some aerodynamic measurements have been made in the past on split-skirt stabilizers in the wind tunnels of the U. S. Naval Ordnance Laboratory (NOL). One of the more extensive research programs of this type was carried out on an ogive cylinder with a split-skirt stabilizer (see Fig. 1). These tests, at subsonic, transonic and supersonic Mach numbers (up to Mach 1.75), included pitch damping, as well as six-component static measurements (Ref. (2)). The results indicated that the increase in drag coefficient was roughly proportional to the angle of skirt opening. The center of pressure moved aft as the skirt opening increased to an upper limit of 45 degrees. Later it was agreed, in discussions between NOL, the U. S. Naval Weapons Laboratory (NWL), the U. K. Royal Aircraft Establishment (RAE) and the Australian Weapons Research Establishment (WRE), to include split-skirt tailed bombs in the joint research program on the flight dynamics of freely falling missiles.

The general principles established during the investigation into the cruciform fin tailed bomb behavior, as described in Reference (1), were followed with the split-skirt designs. Wind-tunnel tests were performed by NOL and from the results of these tests, full-scale evaluation was undertaken at WRE with split-skirt tails fixed open on the M823 basic research body. Further wind-tunnel tests, including tests to measure pitch damping and Magnus forces and moments, were done by NOL (Refs. (3), (4), (5)). In the U. K., feasibility studies were made to assess the engineering aspects of automatically opening split-skirt tails. The purpose of these studies was to investigate production methods and costs. If the fixed split skirts dropped at WRE proved successful, opening split-skirt tails would be provided for trials at WRE to demonstrate high-speed, low-altitude performance by trials in the U. K.

SYMBOLS

C_D	drag coefficient, D/QS
C_ℓ	roll-moment coefficient, M_x/QSd
C_{ℓ_p}	damping-in-roll derivative, $\partial C_\ell/\partial(pd/2V)$
C_m	pitching-moment coefficient, M_y/QSd
C_{m_α}	pitching-moment derivative with respect to angle of attack, $\partial C_m/\partial\alpha$
$C_{m_q} + C_{m_{\dot\alpha}}$	damping-in-pitch derivative, $\partial C_m/\partial(qd/2V) + \partial C_m/\partial(\dot\alpha d/2V)$
C_n	yawing-moment coefficient, M_z/QSd
C_{n_p}	Magnus-moment derivative, $\partial C_n/\partial(pd/2V)$
C_N	normal-force coefficient, $-F_z/QS$
C_{N_α}	normal-force derivative with respect to angle of attack, $\partial C_N/\partial\alpha$
C_x	axial-force coefficient, F_x/QS
C_y	side-force coefficient, F_y/QS
C_{y_p}	Magnus-force derivative, $\partial C_y/\partial(pd/2V)$
d	reference length, maximum body diameter
F_x	component of aerodynamic force along the X axis
F_y	component of aerodynamic force along the Y axis
F_z	component of aerodynamic force along the Z axis
M	Mach number
M_x	rolling moment, moment about the X axis
M_y	pitching moment, moment about the Y axis
M_z	yawing moment, moment about the Z axis

SYMBOLS (Cont.)

p	spin rate, component of angular velocity about X axis
q	pitch rate, component of angular velocity about Y axis
Q	dynamic pressure, $\frac{1}{2}\rho V^2$
r	yaw rate, component of angular velocity about Z axis
S	reference area, $\pi d^2/4$
V	free-stream air speed
X	body axis colinear with the longitudinal axis of the store
Y	body axis normal to the longitudinal axis and in a plane defined by two opposing fins
Z	body axis forming a right-handed triad with the X, Y axes
α	angle of attack
ρ	density of fluid medium
ϕ	roll angle
$\lvert\zeta\rvert$	total angle of incidence

WIND-TUNNEL TESTS

In order to study the flight dynamics of split-skirt tailed bombs using the general principles established in Reference (1), it is necessary to provide highly detailed aerodynamic measurements. From the beginning of this tripartite research there was strong feeling that it would not be sufficient to make only the usual static aerodynamic measurements. Dynamic effects, that is, aerodynamic loads resulting from the changing flow field about the body, would also have to be measured.

In 1963 wind-tunnel measurement techniques were critically examined to check their capability of meeting the requirements of the proposed research program. Static wind-tunnel measurements did not pose any difficulties (Ref. (6)). The measurement of normal force, pitching moment, side force, yawing moment and rolling moment involves only well established test techniques. Wind-tunnel measurements of drag did not appear to be justified because dynamic behavior during the early stages of flight was of greatest significance to the study; dispersion at impact was of relatively little concern.

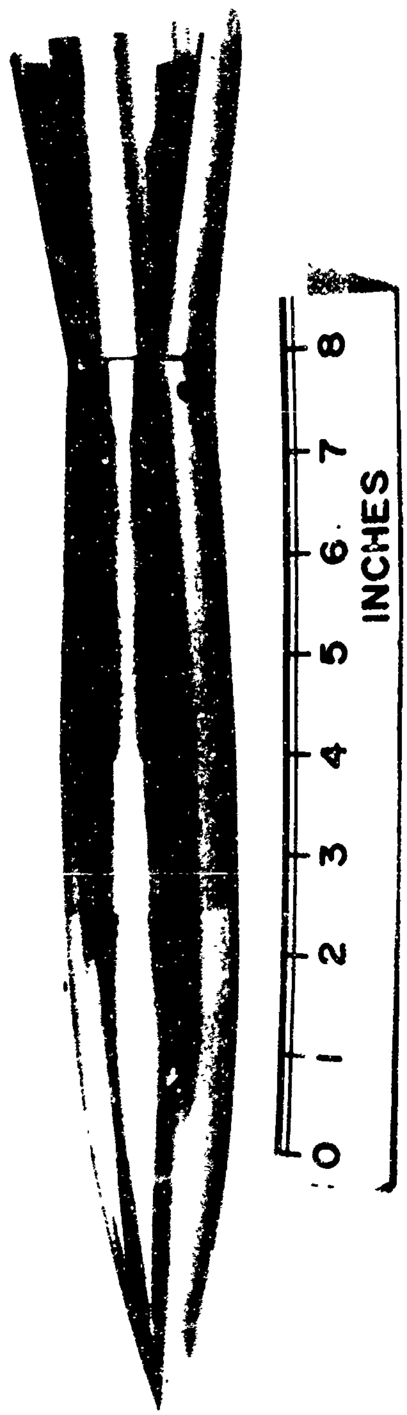


FIG. 2 WIND TUNNEL MODEL OF M823 RESEARCH STORE WITH SPLIT-SKIRT TAIL

During the initial phase of the program, when the need for highly detailed wind-tunnel measurements was first considered, wind-tunnel dynamic measurement methods were far less well established than static measurements. For the split-skirt configuration there was no doubt that pitch-damping measurements would be required. The need for Magnus measurements was indicated by the occurrence of unexpectedly high spin rates in the first flight trial. However, since the stabilizing section of the bomb (split skirts) was nearly a body of revolution, roll-damping measurements were felt to be unnecessary. The Naval Ordnance Laboratory's free-oscillation pitch-damping support was used for the damping measurements and the electric motor-driven Magnus support and balance system for the Magnus measurements.

The static and pitch-damping measurements were carried out in the 16 by 16-inch Naval Ordnance Laboratory Supersonic Tunnel No. 1, which is a one-atmosphere blowdown facility whose relevant flow characteristics are given in Table 1. The Magnus measurements were conducted in the Naval Ship Research and Development Center (NSRDC) 7 by 10-foot Transonic Wind Tunnel. Unlike the NOL facility, this tunnel has the capability of varying the total pressure from one-half to one atmosphere. Some of this facility's relevant flow characteristics for a one-atmosphere total head are also given in Table 1.

The wind-tunnel model used in the static tests is illustrated in Figure 2. This model is one-tenth full scale (14.4 inches long) and is shown with the 15-degree split-skirt opening. Since the forebody remained unchanged throughout the test, only the skirts required replacement. In order to make measurements at various roll angles, the tail was repositioned by releasing a set screw and rotating to the desired position. The assembly was then locked in place by resetting the screw. The base of the model, with the appropriate sting geometry, is shown in Figure 3.

In the static tests, force and moment data were obtained using a five-component internal strain-gage balance. The sting mount was fixed into a rotating sector arm to provide the angle-of-attack traverse for the test. After tunnel flow was established, the model was rotated through the required angle of attack during which time strain-gage signals were sampled and recorded on magnetic tape. The magnetic tape was then fed into a digital-computer data-reduction program. The output of the data-reduction program is a plotting tape from which graphical or tabular records are made of the various aerodynamic coefficients versus angle of attack.

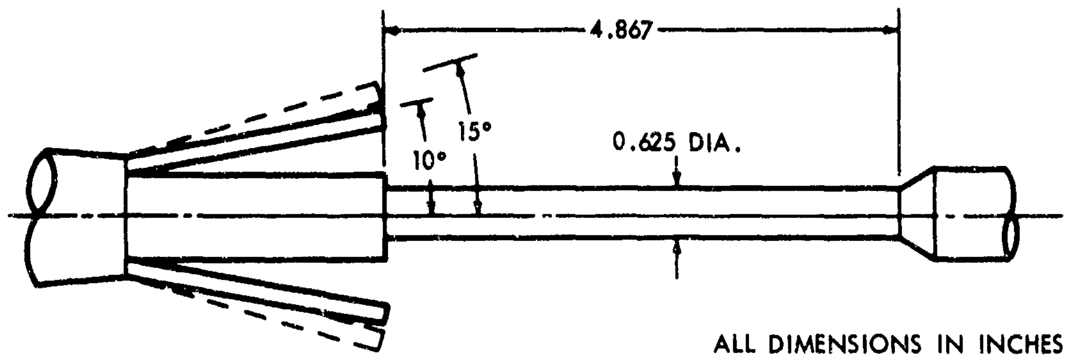


FIG. 3 STING GEOMETRY

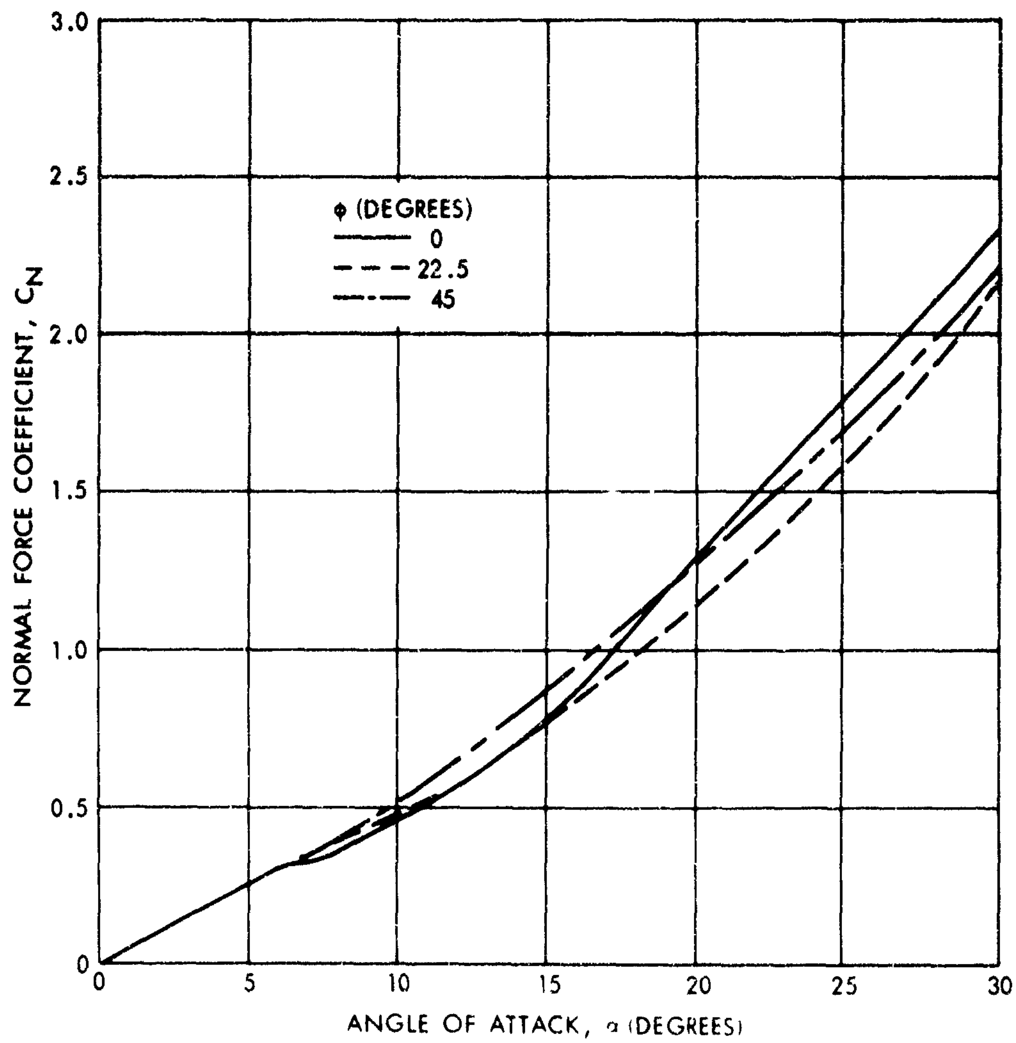


FIG. 4 WIND TUNNEL NORMAL FORCE COEFFICIENT VERSUS ANGLE OF ATTACK FOR THE 10 DEGREE SPLIT-SKIRT CONFIGURATION AT A MACH NUMBER OF 0.85

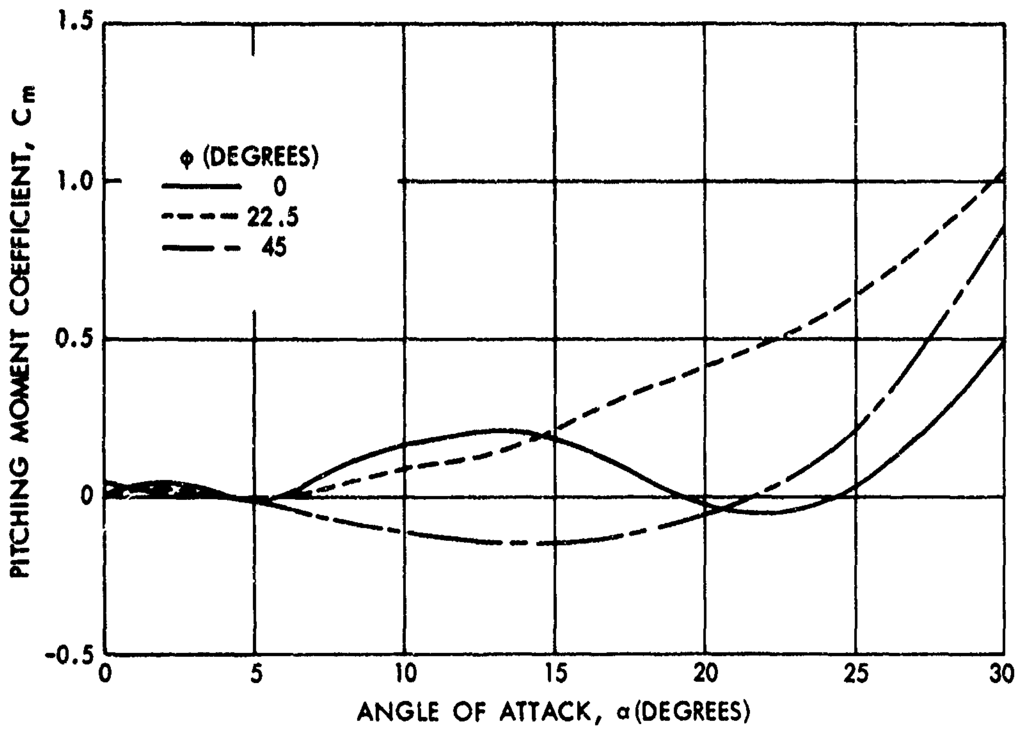


FIG. 5 WIND TUNNEL PITCHING MOMENT COEFFICIENT VERSUS ANGLF OF ATTACK FOR THE 10 DEGREE SPLIT-SKIRT CONFIGURATION AT A MACH NUMBER OF 0.85

Typical plots of the normal-force and pitching-moment coefficients are shown in Figures 4 and 5, respectively, where the moment reference center is at body midpoint. It is interesting to note that the center of pressure at low angles of attack is essentially at the body midpoint. Also, the pitching moment is especially sensitive to body-roll angle at angles of attack above five degrees. Representative side-force and yawing-moment curves are given in Figures 6 and 7. For this configuration the side-force coefficients are rather small and not particularly roll dependent. For example, typical values of side-force coefficients for a conventional cruciform bomb are about 0.4 at 15-degrees angle of attack and at a roll angle of 22.5 degrees. The yawing moment, on the other hand, is extremely roll dependent and at a roll angle of 22.5 degrees has a value quite comparable to that of a cruciform bomb.

All static measurements are available as input for the trajectory program as a function of angle of attack, roll angle and Mach number.

A bomb generally undergoes damped oscillatory motion in response to a disturbance. The damping-in-pitch derivative, $C_{m_q} + C_{m_{\dot{\alpha}}}$ is a measure of the rate at which these oscillations decay. One way to determine this quantity in a wind tunnel is through the method of free oscillations. In the free-oscillation technique the model has unrestricted freedom to rotate about a transverse support shaft. Prior to establishing tunnel flow, the model is constrained at an angle of attack. After flow establishment, the model is released and allowed to oscillate freely about the transverse support. Except for a negligible amount of bearing friction, the torque acting on the model has an entirely aerodynamic origin. From the damped sinusoidal motion it is possible to use a variety of methods to obtain the damping-in-pitch derivative. Regardless of the data-reduction program chosen, a preliminary requirement is to have raw data in the form of pitch angle versus time. The required angular history, in analog form, is provided by a transducer inside the model.

A split-skirt wind-tunnel model is shown mounted on the pitch-damping calibration support in Figure 8. Calibration is a simple "pairing" of transducer output level with the angular measurement indicated by the index on the hoop. Further information on the wind-tunnel pitch-damping support, its calibration and associated data-reduction method, is given in Reference (4). Representative

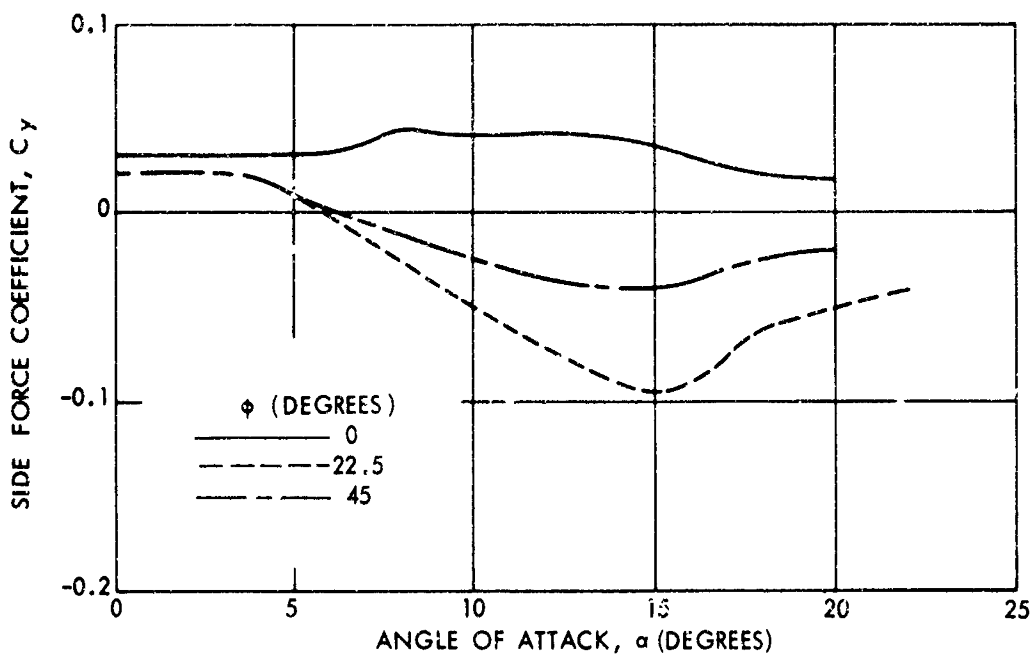


FIG. 6 WIND TUNNEL YAW FORCE COEFFICIENT
VERSUS ANGLE OF ATTACK FOR
THE 10 DEGREE SPLIT-SKIRT CONFIGURATION
AT A MACH NUMBER OF 0.85

damping-in-pitch measurements obtained with this equipment are shown in Figure 9, where it may be seen that incidence dependent effects have not been included. Because of the low accuracy of the data for this particular configuration, it was not practicable to determine these effects, and so the pitch-damping derivative was used in the trajectory program solely as a function of Mach number.

Another type of dynamic phenomenon which can strongly influence bomb performance is commonly referred to as the Magnus effect. In its linear formulation, this effect is defined as that force or moment which is proportional to the product of angle of attack and a nondimensionalized spin rate. Extensions of the basic linear relationship recognize nonlinear variations in the side-force and yawing-moment coefficients with both angle of attack and spin rate. However, the split-skirt configuration indicated a near linear variation of the Magnus moment with spin rate so that attention was confined to determining angle-of-attack nonlinearities.

Magnus measurements were made at the NSRDC 7 by 10-foot Transonic Wind Tunnel and a special balance was constructed for these tests. The split-skirt configuration is shown in Figure 10 mounted in the NSRDC wind tunnel. The sting geometry in the Magnus tests is similar to that shown in Figure 3.

In making Magnus measurements, the model is mounted on the balance which, in turn, is locked to the wind-tunnel splitter plate through the boom (see Fig. 10). When the desired flow conditions are established, an electric motor spins the model to a constant spin rate. Analog signals from the strain gages are sampled and recorded, digitally, on magnetic tape. Ideally, all flow conditions should be constant during this period. In order to make allowance for random phenomena, such as balance vibration and flow perturbations, all measurement samples are averaged to give one reading for each data point. A data point is defined by three numbers in a Magnus test of this type, namely, angle of attack, Mach number and spin rate. After the data point has been obtained through the above sampling procedure, the spin rate is changed and the process repeated. When the spin range has been covered (usually by about six discrete values) the angle of attack is changed and the spin range is again traversed. Upon completion of the angle-of-attack range, the Mach number is changed and the entire procedure repeated.

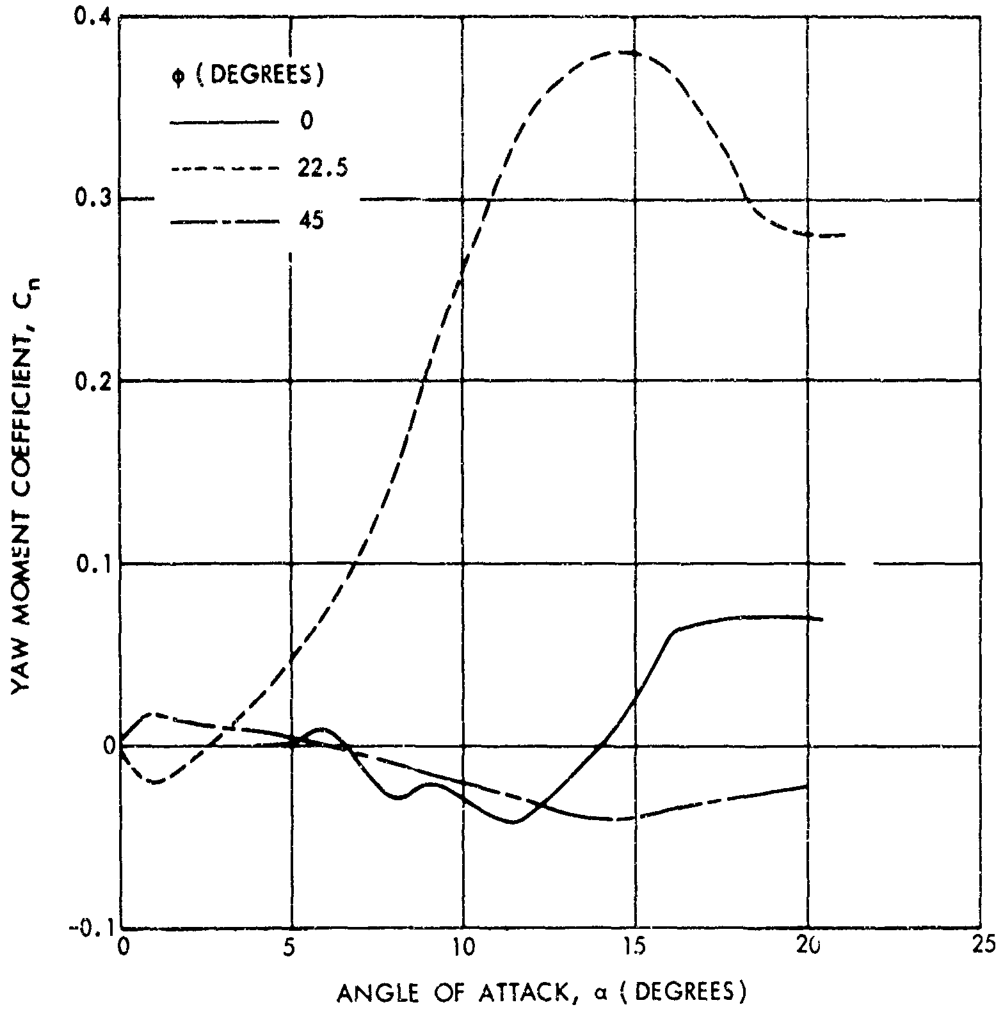


FIG. 7 WIND TUNNEL YAWING MOMENT COEFFICIENT VERSUS ANGLE OF ATTACK FOR THE 10 DEGREE SPLIT-SKIRT CONFIGURATION AT A MACH NUMBER OF 0.85

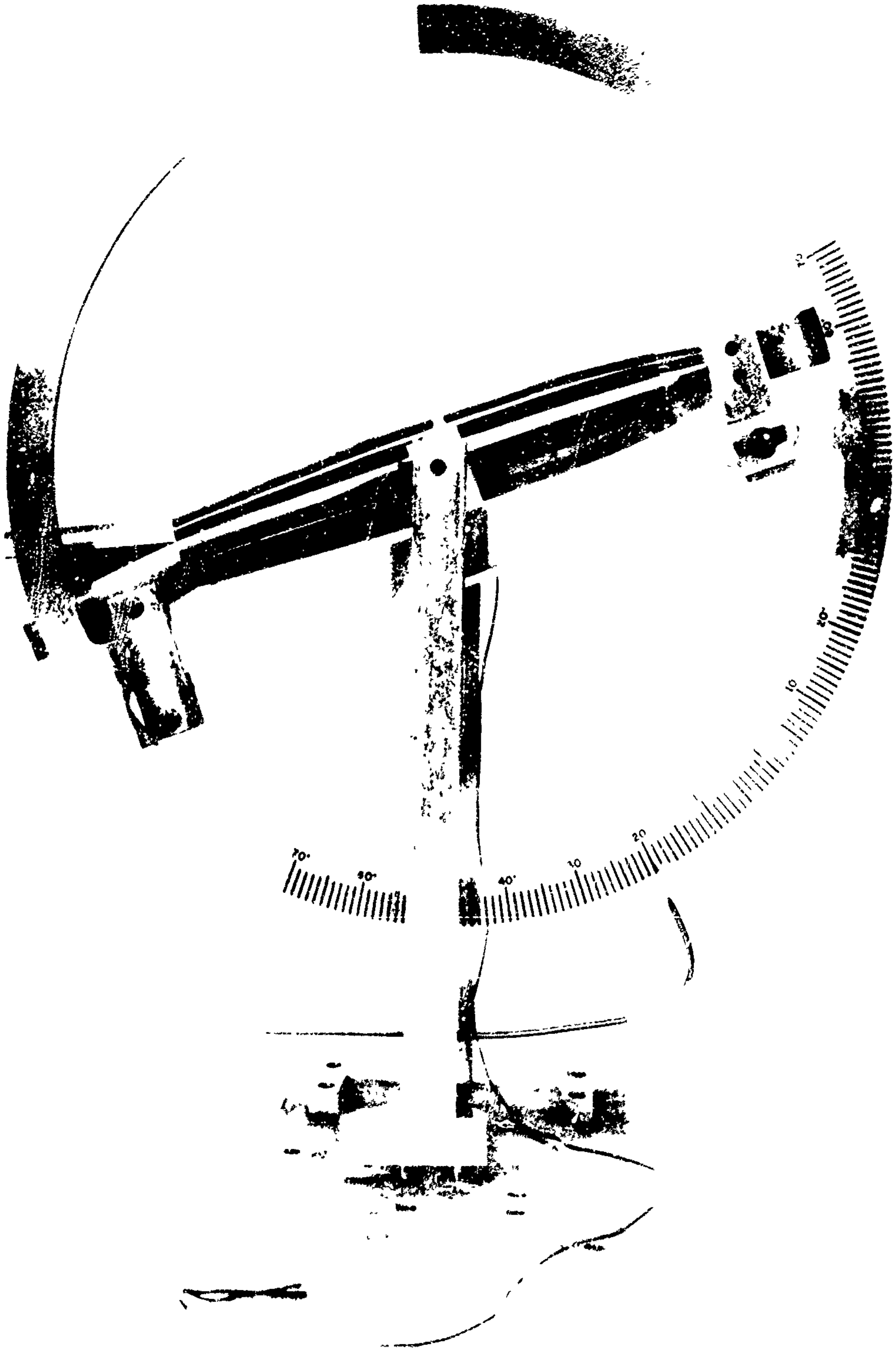


FIG. 8 M82 TEN DEGREE SPLIT-SKIRT CONFIGURATION IN THE [illegible]
CALIBRATION SUPPORT

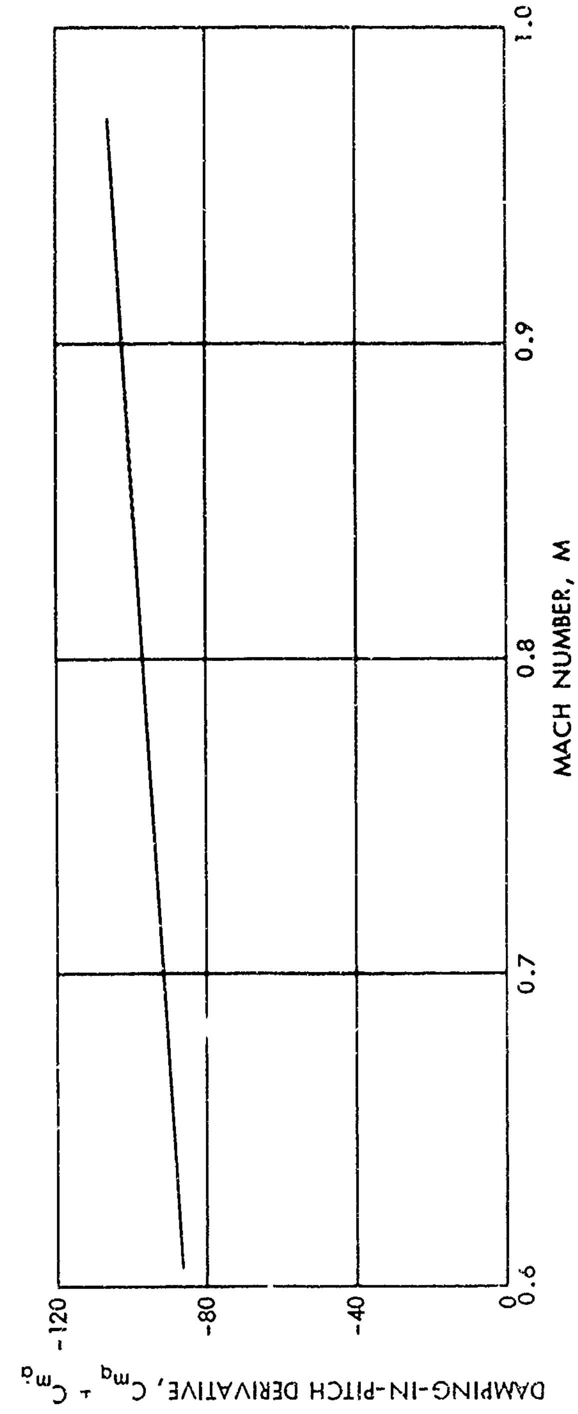


FIG. 9 WIND TUNNEL DAMPING IN PITCH DERIVATIVE VERSUS MACH NUMBER FOR THE 10 DEGREE SPLIT-SKIRT CONFIGURATION

In general, the side-force and yawing-moment coefficients are functions of spin rate, angle of attack and Mach number but, as mentioned above, the split-skirt configuration had side-force and yawing-moment coefficients that were linear with spin rate. Thus, it was possible to fully describe the Magnus effect in terms of the spin dependent derivatives C_{y_p} and C_{n_p}, that is, the derivatives of the side-force and yawing-moment coefficient with reduced spin rate, pd/2V.

Representative Magnus measurements for the 10-degree split-skirt configuration are given in Figure 11, where the moment reference center is at the body midpoint. It is easily shown that Magnus center of pressure moves aft with increasing angle of attack to about 80 percent of the body length from the vertex at 15-degrees angle of attack. This measurement is typical of results obtained with artillery shells, which is not surprising considering the shape of the bomb. A comprehensive set of Magnus measurements of all configurations studied in this program is contained in Reference (5).

FLIGHT TRIALS AND RESULTS

Full-scale instrumented bomb trials were conducted at Woomera, Australia, to obtain free-flight trajectory data and dynamic behavior of the research stores. Each round was fitted with a spin sensor, yaw meter, accelerometers and a telemetry sender to measure the effects of release disturbance on the subsequent flight. Information telemetered from the research stores gave a measure of spin rate and of the amplitude, frequency and damping of oscillations experienced throughout the period of fall, from release to impact. In addition, wing tip and bomb bay cameras were installed on the "bombing" aircraft to record the pitching and yawing attitudes reached by each round in response to the release disturbance. Finally, trajectories were obtained by means of Contrave kine-theodolites, enabling the determination of missile position and speed. The true air speed and Mach number were then found from a knowledge of the appropriate meteorological data.

The trials program included three rounds numbered 739, 740 and 741, respectively, which were manufactured at WRE and the method of construction adopted is shown in Figure 12. Basically, the streamlined M823 body comprised five cast-aluminum alloy sections, four of which were flanged and fitted with studs to facilitate assembly. To maintain a "clean" external surface, the body sections were bolted together by studs placed below the skin line, making it necessary to

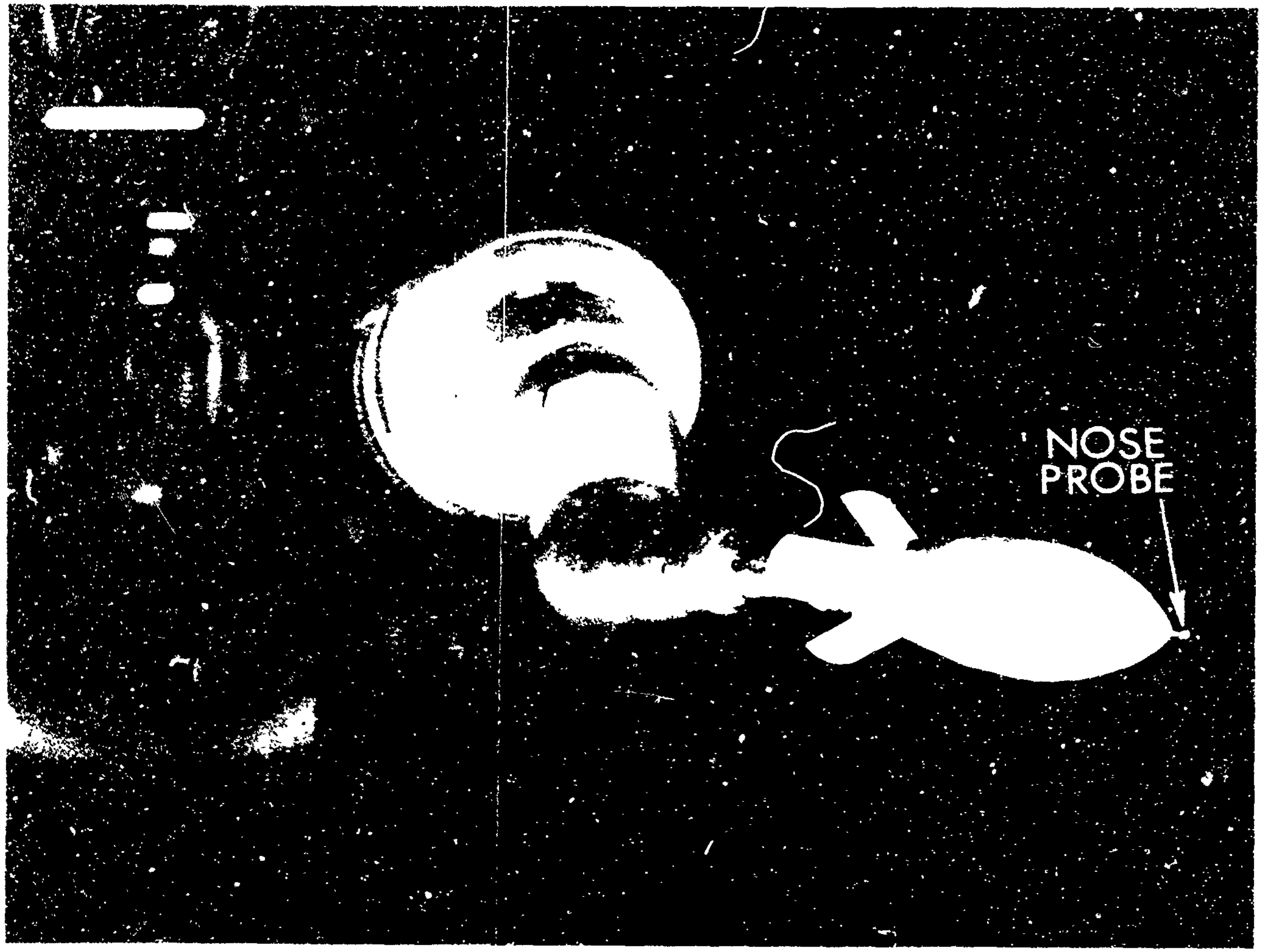


FIG. 10 M823 MAGNUS MODEL WITH SPLIT-SKIRT STABILIZER
IN NSRDC TRANSONIC WIND TUNNEL

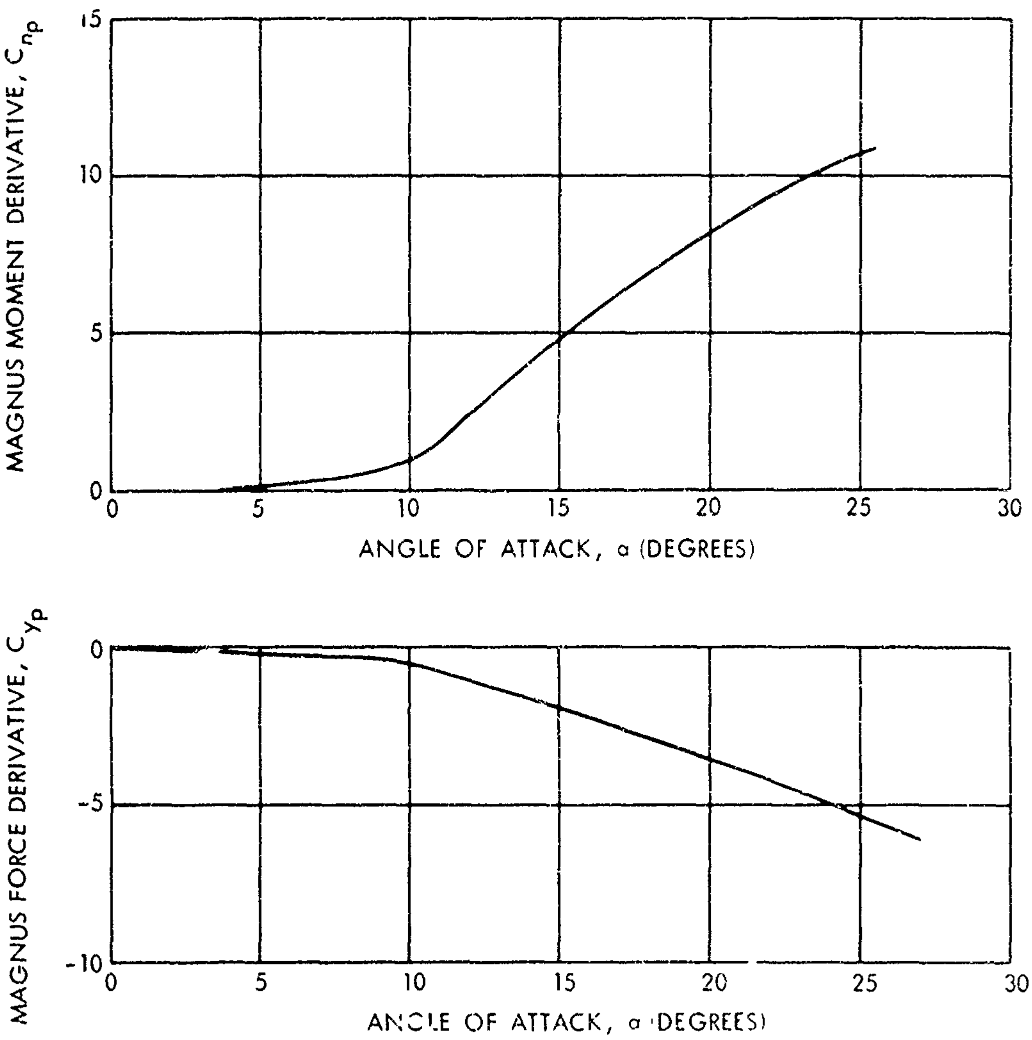


FIG. 11 WIND TUNNEL MAGNUS FORCE AND MOMENT DERIVATIVES VERSUS ANGLE OF ATTACK FOR THE 10 DEGREE SPLIT-SKIRT CONFIGURATION AT A MACH NUMBER OF 0.85

assemble the store progressively from the aft end with a threaded nose cone giving final closure of the vehicle. The telemetry sender was installed as far forward as possible to facilitate maintenance. The total weight of the complete streamlined body was kept below 400 pounds, leaving approximately 450 pounds for the disposition of ballast needed to vary the c.g. position and moment of inertia. Body alignment was maintained by ensuring that the flanged ends of the cast sections were machined square with their individual axes of symmetry.

The four skirt panels, which comprised the stabilizer, were fabricated from aluminum alloy sheet and attached to the body base by means of fixed links to set the required skirt opening angles. Because it was not practicable to house telemetry aerials in this stabilizer arrangement, spike aerials were radially mounted in the vicinity of the telemetry sender. Physical properties of the three rounds, together with details of the trials release and impact conditions are given in Table 2 and Figure 13. It may be seen in Figure 13 that the skirt panels of round 741 were modified by fin-like extensions or flanges. This change was introduced as a "quick-fix" to offset the adverse effects of yaw-induced forces and moments because rounds 739 and 740, with unflanged skirt panels, exhibited very poor dynamic performance.

Measurements made during the free-flight trials are as follows:

1. Ground-based measurements of trajectory

2. Measurements made by instruments carried in the test vehicles

3. Observation of the release disturbance from aircraft cameras

4. Meteorological measurements.

The methods used to obtain these measurements are outlined in Reference (1), together with an assessment of the accuracy achieved under the operating conditions at the Woomera Range.

RESULTS OF INSTRUMENTED BOMB TRIALS

Each test vehicle was released singly, in level flight, from the same station in the bomb bay of a Canberra aircraft. To assess the overall ballistics performance of individual rounds, the observed impact conditions were compared with those predicted on the IBM 7090

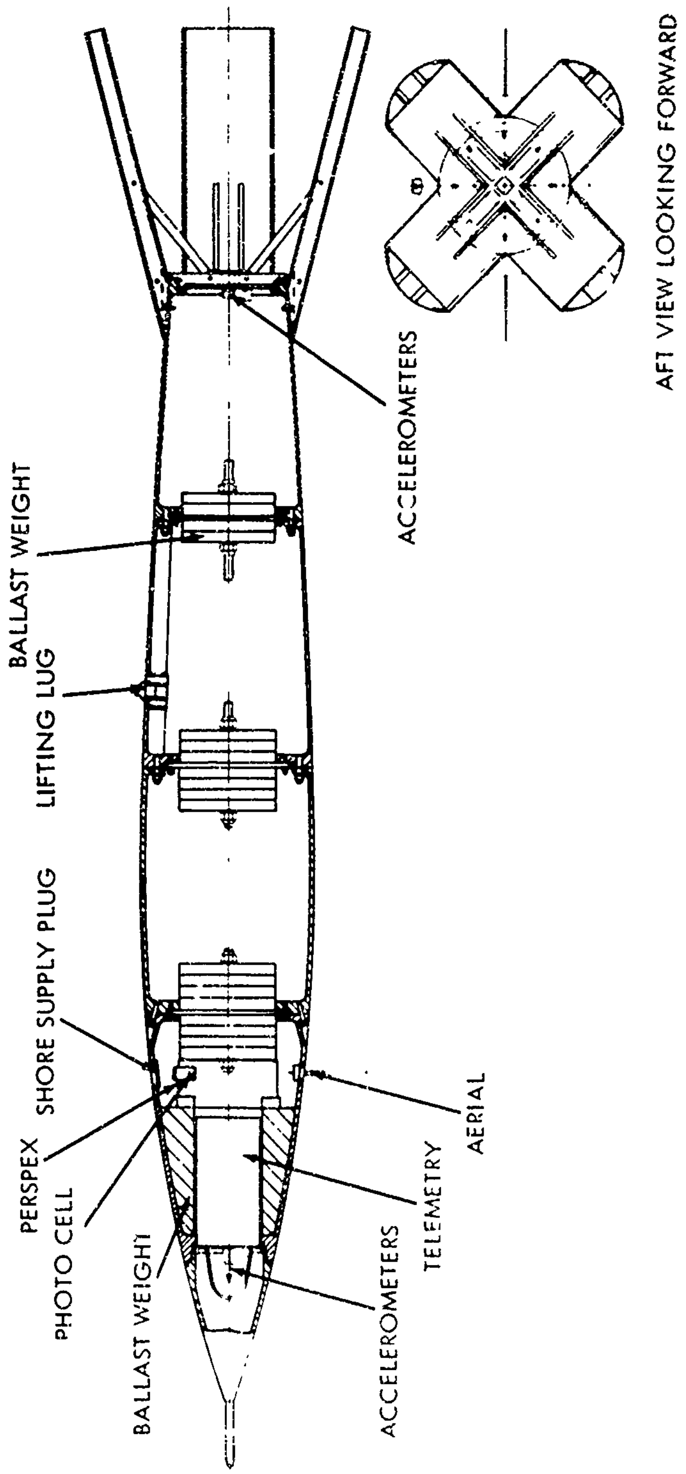
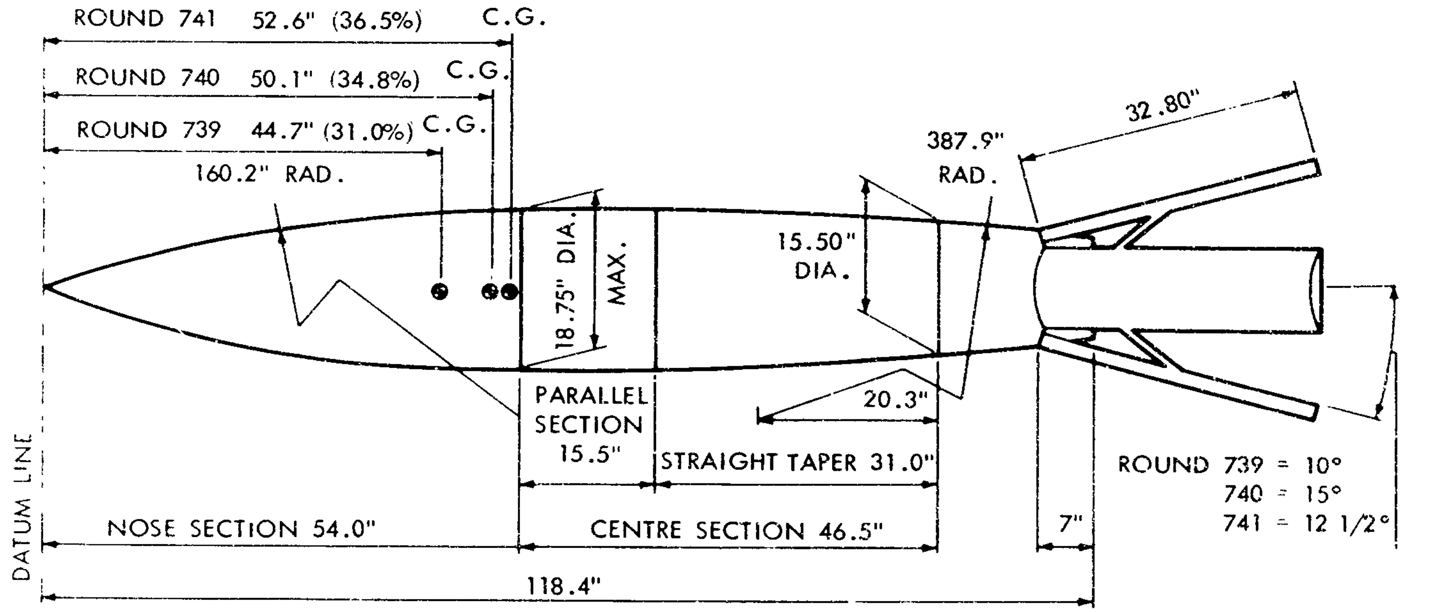
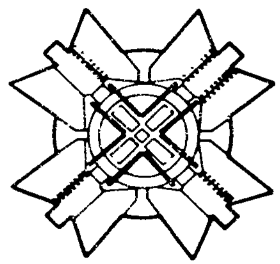


FIG 12 GENERAL ASSEMBLY OF M 823 TEST VEHICLE WITH SPLIT SKIRT STABILIZER

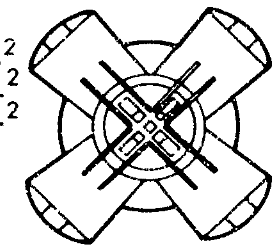


NOTES:

1. VEHICLE WEIGHT — ROUND 739 = 939 lb.
   ROUND 740 = 916.5 lb.
   ROUND 741 = 962 lb.
2. MOMENT OF INERTIA IN PITCH — ROUND 739 = 171.3 SLUG FT.^{2}
   ROUND 740 = 209.1 SLUG FT.^{2}
   ROUND 741 = 263.3 SLUG FT.^{2}
3. MOMENT OF INERTIA IN ROLL — ROUND 739 = 8.8 SLUG FT.^{2}
   ROUND 740 = 8.6 SLUG FT.^{2}
   ROUND 741 = 9.2 SLUG FT.^{2}



REAR VIEW — ROUND 741



REAR VIEW — ROUND 739

FIG. 13 M823. SPLIT-SKIRT TEST VEHICLES

computer using the measured release conditions and meteorological data, together with a measured drag function for the bomb (Ref. (1)).

Particle trajectories were computed initially assuming that the bomb moved in a nonrotating field with a constant gravitational attraction everywhere perpendicular to a plane; corrections for the earth's rotation, the variation of gravity with height and the variable direction of gravity (spherical earth) were subsequently estimated and subtracted from the observed impact data to give the impact deviations in range, line and time of fall listed in Table 2. These corrections were calculated for vacuum conditions because such an approximation was found to give results with sufficient accuracy.

In the following paragraphs a brief description of the flight behavior is given for each test vehicle. Comparisons of free-flight and wind-tunnel measurements of the aerodynamic coefficients and theoretical studies of dynamic behavior are made in later sections.

Round 739: Skirt Panel Angle 10 Degrees. With skirt panels set at 10 degrees, this round had the least effective stabilizer of the three configurations which were tested; and it was, therefore, considered necessary to place the center of gravity well forward. A value of 31 percent body length was chosen and under this condition the response to the release disturbance was quite clean, giving an initial pitch amplitude of approximately 15 degrees. The spin rate increased steadily after release until resonance occurred at about 10 seconds when the incidence diverged rapidly to about 30 degrees. This behavior was consistent with catastrophic yaw which persisted for a further 10 seconds. At about 20 seconds the round broke out of resonance, the spin rate increased sharply, and the yawing amplitude dropped to somewhat less than 10 degrees. Throughout the remaining fall, a coning motion of slowly increasing amplitude persisted and the spin rate continued to increase to a maximum of 36 r.p.s. shortly before impact. The general pattern of spin rate and yawing motion may be seen in Figures 14 and 15, which indicate a progression of flight dynamic behavior from resonance and catastrophic yaw to nonlinear Magnus instability.

Round 740: Skirt Panel Angle 15 Degrees. For this round the skirt was opened to an angle of 15 degrees and the c.g. correspondingly set at 34.8 percent body length, giving a static margin comparable with that of round 739. Response to the release disturbance was quite normal but the spin rate increased rapidly to about 0.4 r.p.s. in the first five seconds. A near constant trimmed incidence of approximately 12 degrees developed and was maintained throughout

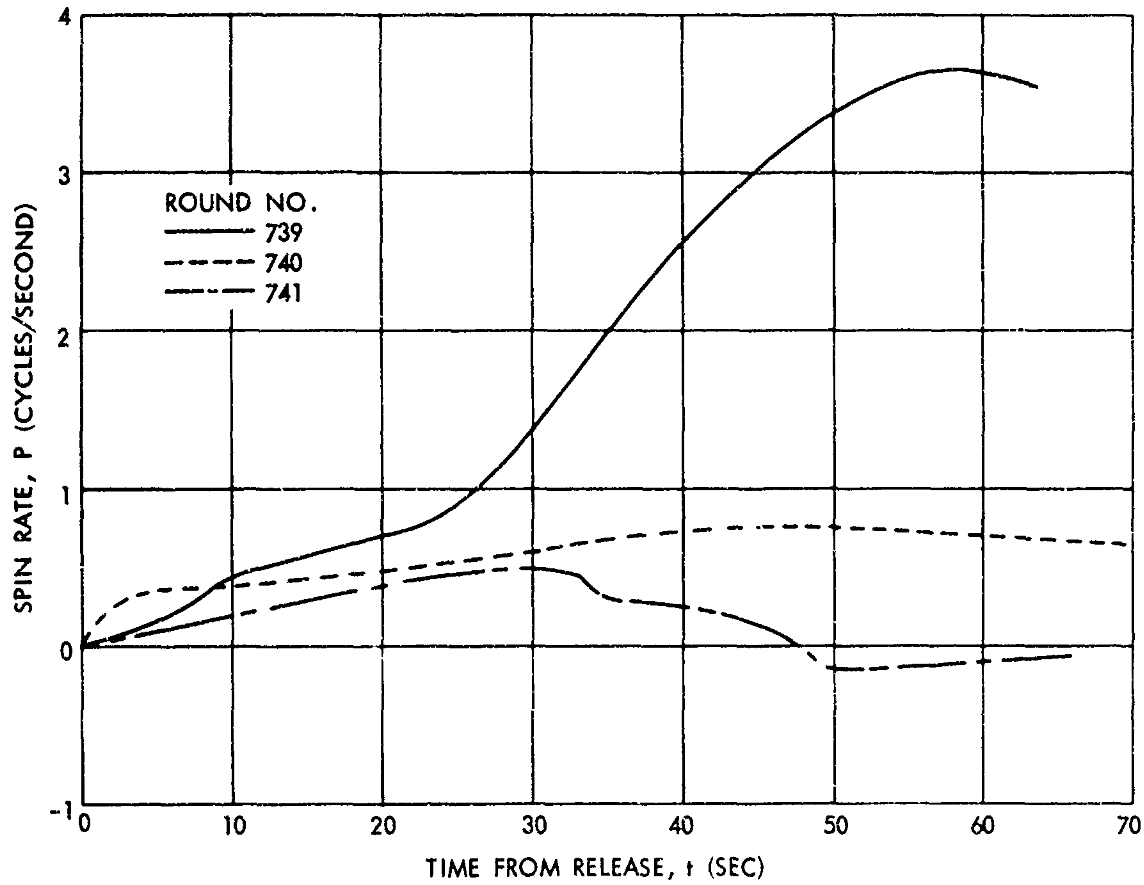


FIG. 14 SPIN RATE HISTORIES OF ROUND NUMBERS 739, 740 AND 741

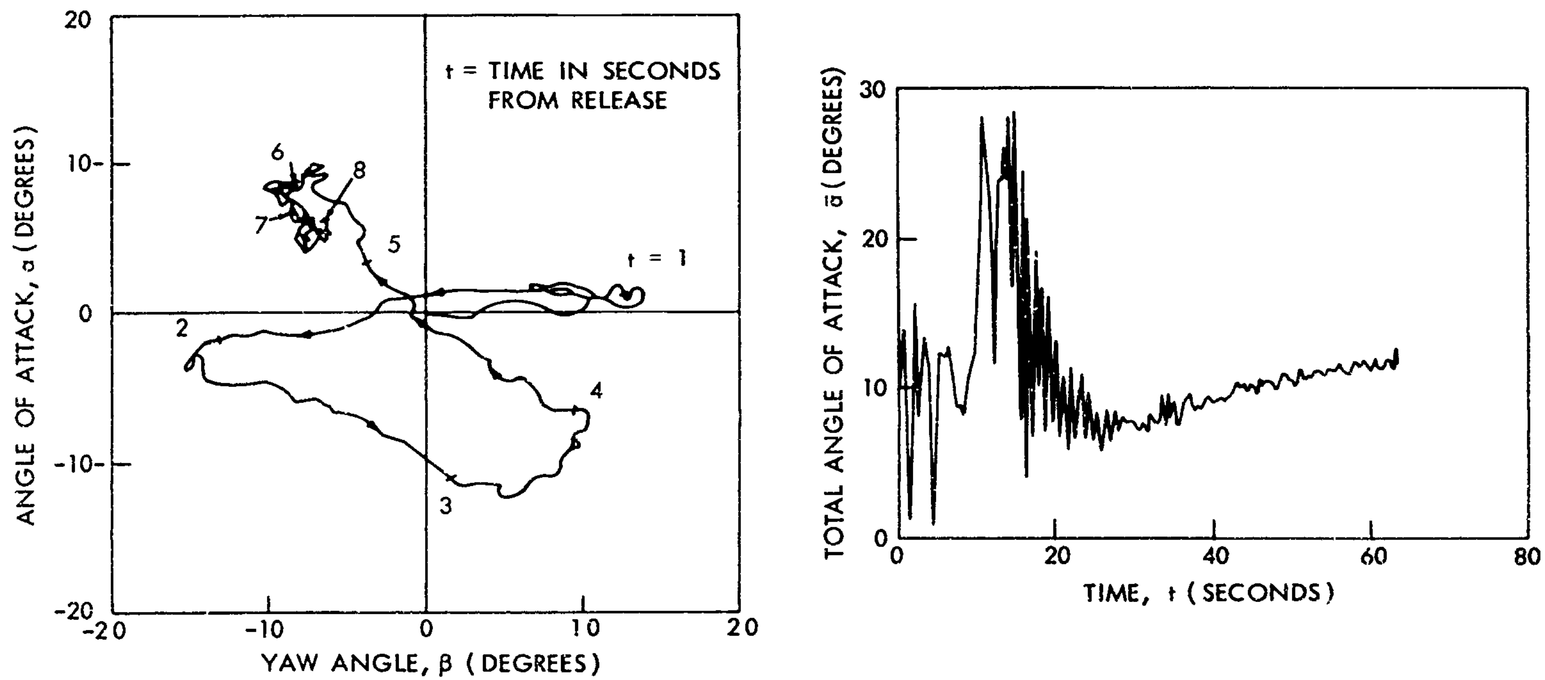


FIG. 15 FLIGHT HISTORY OF ANGLE OF ATTACK REFERRED TO BODY AXES, ROUND 739

the fall, giving rise to a steady coning motion about the flight path. This behavior was again typical of catastrophic yaw from which the round did not recover, as indicated by the histories of spin rate and angle of attack shown in Figures 14 and 16.

Round 741: Modified Skirt Panel Angle 12.5 Degrees. As mentioned previously, in view of the poor flight dynamic performance exhibited by rounds 739 and 740, it was decided to attempt a quick fix by fitting flanged-skirt panels to round 741. These proved to be most effective in reducing the adverse roll-yaw effects and, as shown in Figure 14, the spin rate did not exceed 0.5 r.p.s. The release oscillation rapidly decayed and the round fell to impact with virtually no residual yawing motion.

An indication of the influence of drag due to large amplitude oscillations upon the flight histories of the three rounds is given in Figure 17, which shows the variations of Mach number throughout each flight trial.

FREE-FLIGHT AERODYNAMIC ANALYSIS

Dependence of the measured aerodynamic forces and moments upon incidence, roll orientation, and angular velocity is determined by using a least-squares method to fit the flight data to a mathematical model of the force and moment system developed by Maple and Synge (Ref. (7)). A detailed description of the methods which were used in analyzing the flight data and the results of the split-skirt trials may be found in References (8) and (9), respectively.

Basically, Maple and Synge represent the overall force and moment system by a complex Taylor series expansion and make use of the properties of rotational and reflectional symmetry to systematically eliminate particular terms. Two assumptions are made concerning the aerodynamic forces and moments acting on a body. These are:

1. that they depend only on the instantaneous values of the linear and angular velocities of the body, and

2. that they are analytic functions of the components of these two velocities.

The split-skirt configuration is assumed to have the same properties of reflectional and rotational symmetry as the cruciform-tail configuration. The application of the theory is, therefore, identical and the representations used were as follows:

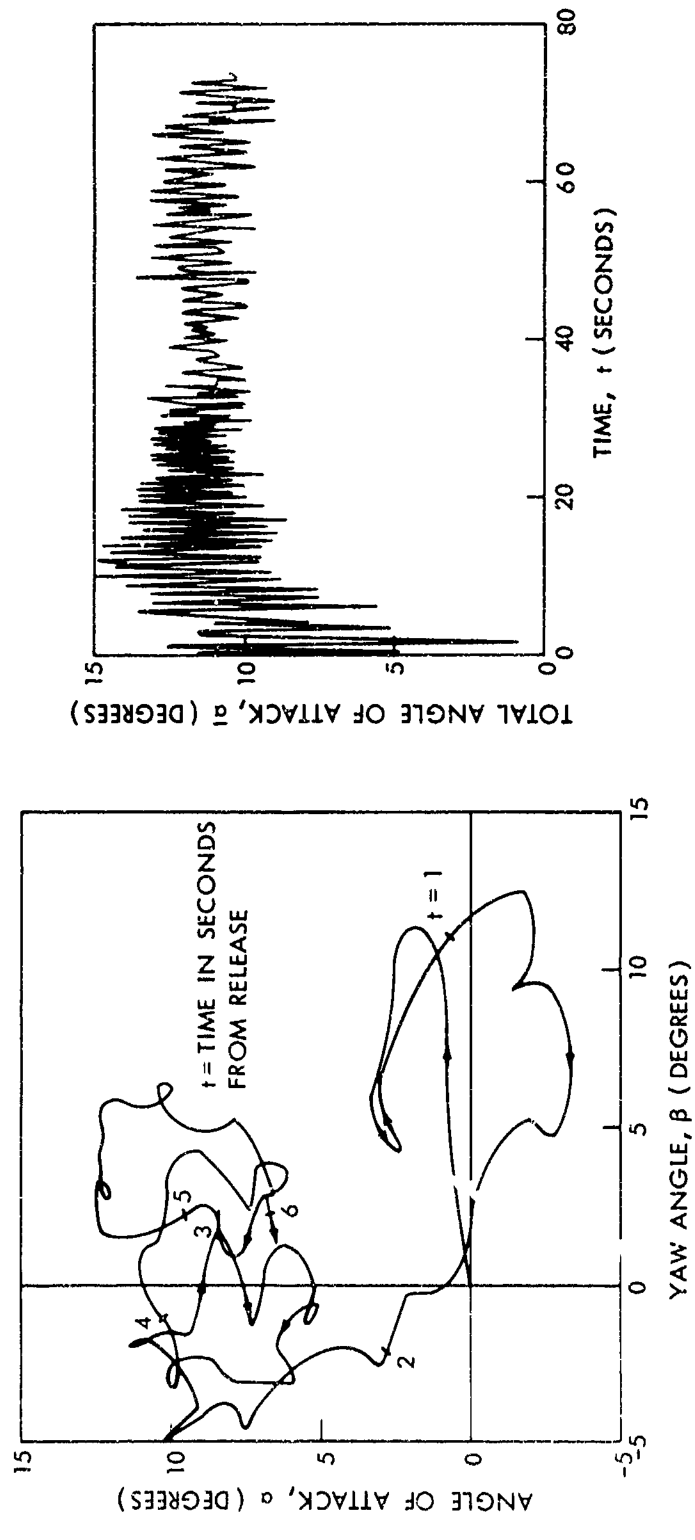


FIG. 16 FLIGHT HISTORY OF ANGLE OF ATTACK REFERRED TO BODY AXES, ROUND 740

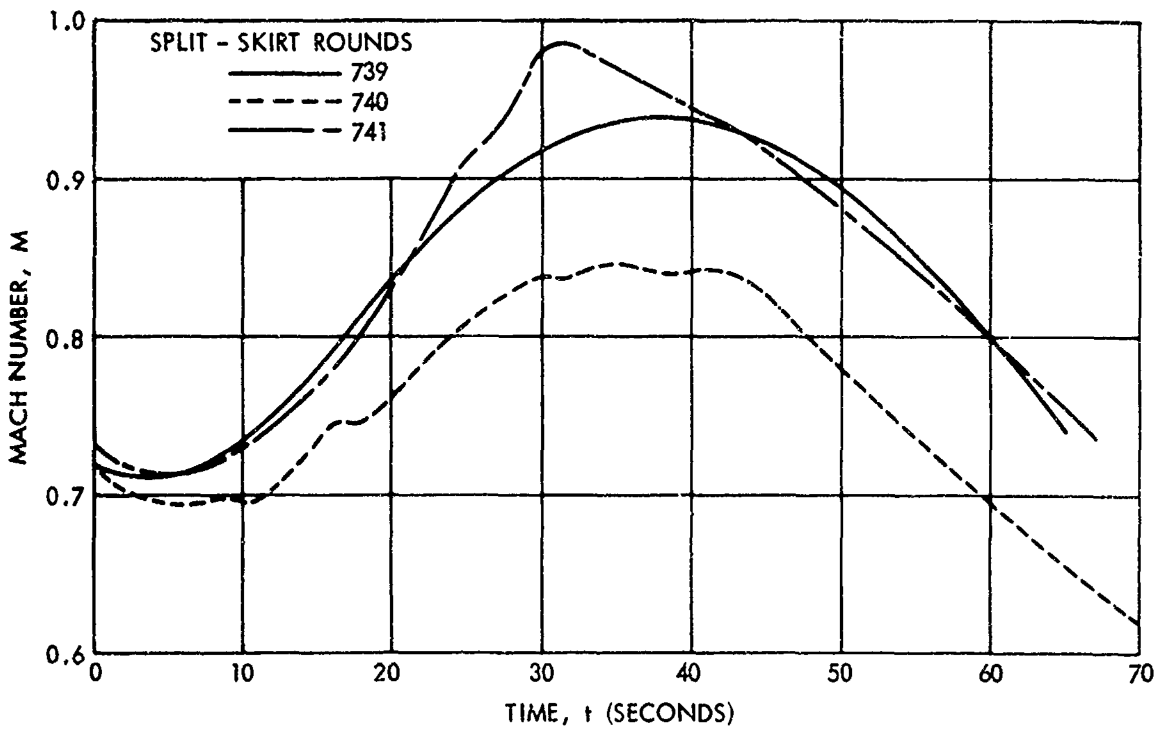


FIG. 17 MACH NUMBER HISTORIES OF SPLIT-SKIRT ROUNDS 739, 740 AND 741

Static-restoring moment and normal-force coefficients defined by similar expressions of the form:

$$a_1 \tan|\zeta| + (a_2 + a_3 \cos 4\phi) \tan^3|\zeta| \quad (1)$$

Static-side moment and side-force coefficients defined by similar expressions of the form:

$$a_3 \sin 4\phi \tan^3|\zeta| \quad (2)$$

Magnus moment and force coefficients defined by similar expressions of the form:

$$b_1 \tan|\zeta| \quad (3)$$

where the least squares coefficients, a_1, a_2, a_3 and b_1, depend upon Mach number and absolute roll rate only. The magnitude of the angle of incidence vector is $|\zeta|$, and ϕ is the angular orientation of a fin relative to the plane of the angle of incidence (defined positive for a clockwise rotation viewed from the rear). Whatever representation of pitch and yaw damping was adopted, at the best, only qualitative results could be obtained. The particular parameters were sensitive to small variations in the data. To prevent erroneous values affecting the complete representation, constant values for pitch- and yaw-damping coefficient derivatives were estimated from static wind-tunnel data. These values are as indicated below:

	Moment	Force
Pitch	$C_{m_q} + C_{m_{\dot{\alpha}}} = -80$	$C_{z_{\dot{\alpha}}} = 9$
Yaw	$C_{n_r} + C_{n_{\dot{\alpha}}} = -80$	$C_{y_{\dot{\alpha}}} = -9$

Because accurate values of roll acceleration could not be obtained, the rolling moments were not analyzed.

In general, the oscillations of the test vehicles were irregular and so, to reduce any biasing effect towards a particular range of incidence, a region of the data was chosen for each round over which four complete cycles took place (peak to peak defining a complete cycle). Since the storage capacity of the IBM 7090 was not sufficient

to permit use of every telemetry data point in the least squares fit, every second point was used. However, all the points were still used in the smooth process.

The ranges of time from release, Mach number, roll rate, angle of incidence, and roll orientation over which analyses were carried out are given in Table 3 for both rounds considered. The skirt angle and Reynolds number (based on body diameter) are also given in this table.

Roll lock-in occurred with round 740, and to a lesser extent with round 739, so that a complete cycle of roll orientation was not achieved over the flight periods analyzed. Normally, zero errors in the total force and moment coefficients caused by extrapolation of the total force and moment coefficients to zero incidence are included in the force and moment representations, and static coefficients determined by the least squares coefficients, a_1, a_2, a_3, are adjusted to zero for zero angle of incidence. The effect of these errors is small, provided at least a complete cycle of roll orientation is achieved during the period of analysis. With round 740, these errors are large and, because of roll lock-in, the effect is magnified beyond acceptable limits.

So far as overall accuracy of the free-flight data fitting technique is concerned, there are errors introduced by the airborne sensors and the associated signal transmission by telemetry, and errors arise because the mathematical model does not truly represent the physical reality. Incidence meter calibrations account for most of the former source of error and amount to an error of up to five percent within the range of incidence considered. The magnitude of errors from the latter source is unknown but with round 739, reduction of order in the power series in tan $|\zeta|$ from five to three made, roughly, a 10 percent difference in the normal-force coefficient at 10-degrees incidence.

COMPARISON OF FREE-FLIGHT AND WIND-TUNNEL COEFFICIENTS

Derivation of free-flight aerodynamic data was not attempted in the case of round 741 because this round experienced large angles of incidence only during a very short period immediately following release. Furthermore, no wind-tunnel data were available for comparison. Rounds 739 and 740, having respective skirt angles of 10 degrees and 15 degrees, experienced substantial periods of large amplitude motion (see Table 3), and suitable wind-tunnel data were available for comparison. However, there were slight differences between the free-flight rounds and wind-tunnel models; the free-flight rounds had a protruding nose probe for the purpose of recording angles of attack and side slip, an extension of the rear end of the bomb body into the open end of the split-skirt configuration, and struts connecting this extension with the skirts.

Wind-tunnel results for the normal-force and restoring-moment coefficients were taken from NOL tests at a Reynolds number of approximately 0.6×10^6 (based on body diameter) and Mach number 0.8 for the 10-degree split skirt. Comparisons of free-flight measurements of round 740 with wind-tunnel data are not shown because of the reliability of the free-flight measurements caused by the previously mentioned effect of roll lock-in. Comparisons of free-flight measurements of round 739 with wind-tunnel data are shown in Figure 18. Within the range of angle of incidence experienced during the analyzed flight period, the normal-force coefficient shows good agreement with wind-tunnel data. However, it is suspected that the poorer agreement observed for the restoring moment is caused by changes in center-of-pressure position due to the differences between the free-flight rounds and wind-tunnel models.

Data on side-force, side-moment and Magnus effects have not been presented because of the poor accuracy of the flight data.

FLIGHT SIMULATION

Predicted motions of the research store fitted with a fixed-cruciform tail have shown a high degree of correlation with the observed flight histories (Ref. (1)). However, as might be expected, detailed agreement has never been achieved. For the split-skirt stabilizer, round 739 was chosen as the most suitable example for flight simulation and care was taken to introduce the actual air density and speed of sound data recorded at the range site at the time of flight trial. Also, since wind-tunnel data did not indicate

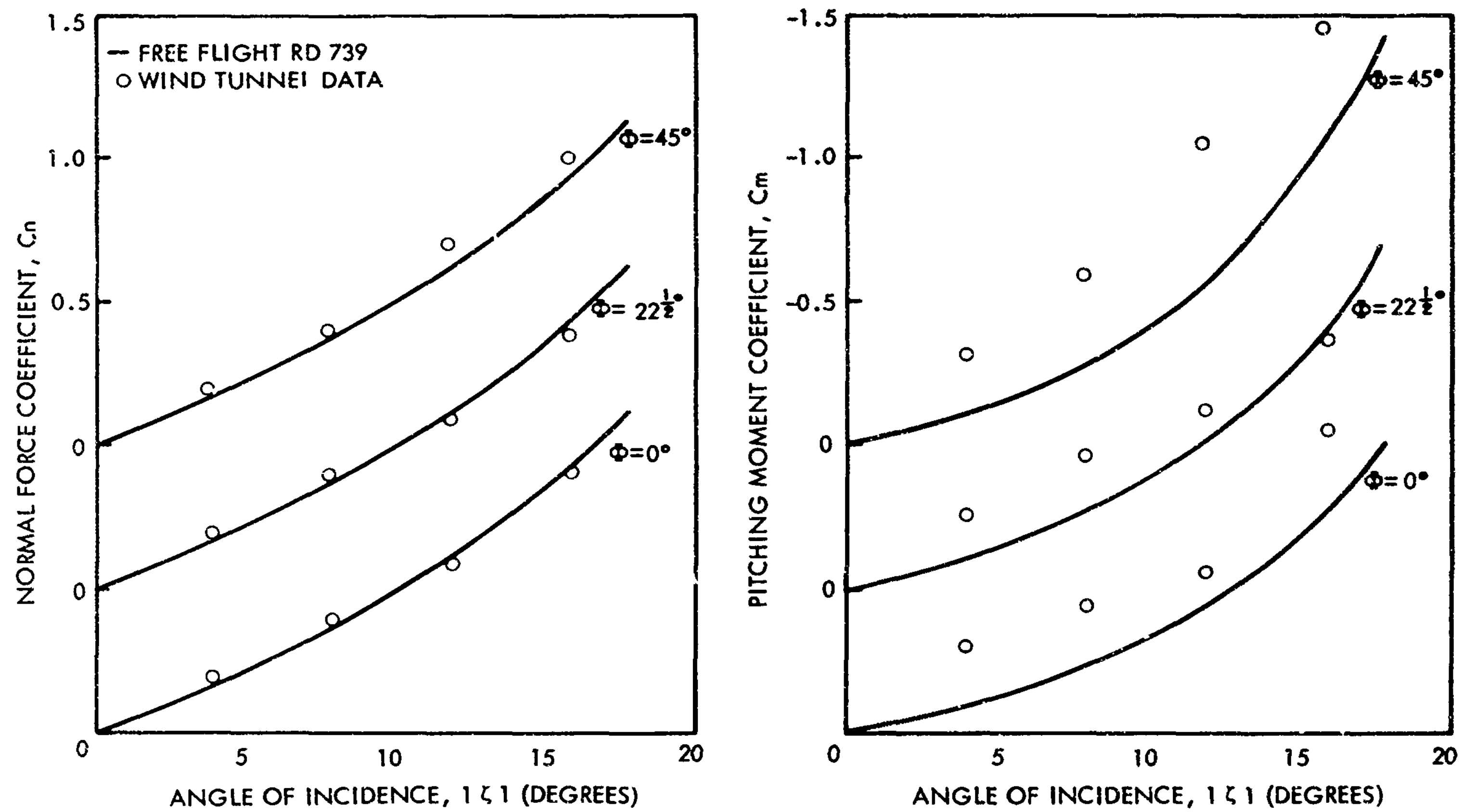


FIG. 18 COMPARISON OF FREE FLIGHT AND WIND TUNNEL MEASUREMENTS ON ROUND 739: VARIATION OF NORMAL FORCE AND PITCHING MOMENT COEFFICIENTS WITH ANGLE OF INCIDENCE FOR A MACH NUMBER OF 0.8.

an appreciable roll torque acting upon the model, it was necessary to remove the differential equation describing the roll history of the store and make provision for introducing round 739's measured spin rate into the program in tabular form as a function of time.

All the aerodynamic data were taken from References (3), (4) and (5). These measurements were made on a configuration which did not have a nose-mounted yawmeter probe. As mentioned earlier, the free-fall vehicle, on the other hand, had a yawmeter probe. Subsequent tests of the M823 body with a fixed-cruciform stabilizer have shown that the effects of the probe can be significant, especially on the induced forces and moments and on the Magnus force and moment. It is unfortunate that the simulation could not include the influence of the probe and, consequently, some doubt must remain over the detailed flight comparison. Finally, since no drag data were available from wind-tunnel tests, the axial-force coefficient was estimated from the bomb axial accelerations measured during the actual drop.

For the computer simulations, it was decided to initiate the prediction approximately two seconds after release from the aircraft when the effects of the flow field about the aircraft could be ignored. The results of starting the simulation at this point, using the wind-tunnel pitching-moment data, were not at all satisfactory. The computer model appeared to exhibit a higher degree of static stability than that of the free-fall vehicle. After examining the aerodynamic coefficient obtained from the instrumented free-fall store measurements, as shown in Figure 18, it was decided that appropriately reduced values for both the static and dynamic pitching-moment coefficients would be more representative for use in the computer simulations. The results of the simulation attempts, using these new values, gave quite a fair degree of correlation as indicated in Figure 19, but it was not found possible to reproduce the effects of Magnus instability which apparently occurred later in the flight of round 739. Although the simulation of catastrophic yaw in the first 12 seconds of flight was quite realistic, it is believed that the nose probe did have a strong aerodynamic influence on the induced forces and moments. Nevertheless, the flight simulation has provided considerable insight into problems associated with the design of split-skirt stabilizers.

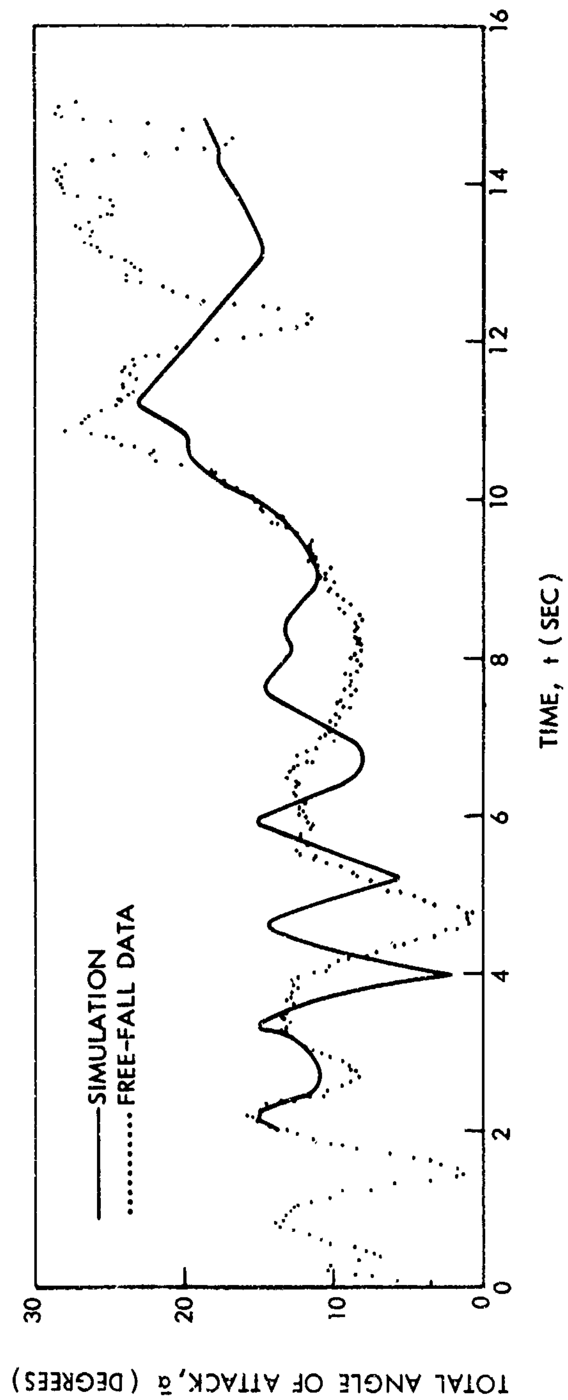


FIG. 19 COMPARISON OF MEASURED AND SIMULATED ANGLE OF ATTACK HISTORY FOR ROUND 739

MECHANICAL FEASIBILITY

Design feasibility study contracts were put out to three U. K. contractors who worked to a design specification written by RAE for an automatically opening split-skirt tail. The specification detailed the design parameters for a tail which would fit the M823 research body, but which would also incorporate any necessary operational features. The tail segments were to be opened in unison on release from the aircraft and were to have two opening angles automatically selected. For low-drag operation the first angle could lie within the range of 10 to 45 degrees. The second opening angle, for the high-drag case, would lie between 60 and 80 degrees. In the low-drag mode the tail was required to be locked in place within 0.15 seconds of release. It is necessary to deploy the segments rapidly because of the lack of stability of the vehicle with the segments closed. In the case of high-drag operation, the initial opening rate should again be rapid but subsequent movement of the arms may be slowed to limit shock loads. The power required to deploy the stabilizer was contained within the tail assembly.

Figure 20 shows a sketch of a typical installation. Each segment of the tail consists of a quadrant of a cylindrical shell with a stiffening member incorporating a hinge. The segments are operated by an annular arm mounted concentrically about the control tube which contains the arming unit. The ram, powered by two gas-producing cartridges, is connected through links to levers formed on the flap hinges. The arms are opened to the selected one of two positions, determined by locking the ram at the opposite point of its travel. The mode of operation is as follows: the first cartridge discharges into a cylinder and at the same time unlocks the flaps. The piston moves into the low-drag position and is locked. If the high-drag position has been selected this same operation takes place and, after a pause in the first position, the second cartridge discharges into the cylinder causing as it does, a subsidiary mechanism to release the lock on the piston. This allows the ram to move to the end of the cylinder.

The tail could weigh approximately 190 pounds, compared with the 180 pounds of the normal fixed-fin tail of the research vehicle. Cost estimates were only made for the small number of vehicles necessary for this research program. These figures would be misleading if compared with the cost of a standard bomb tail, but it is clear that the split-skirt stabilizer, as described here, would cost considerably more than the equivalent cruciform tail.

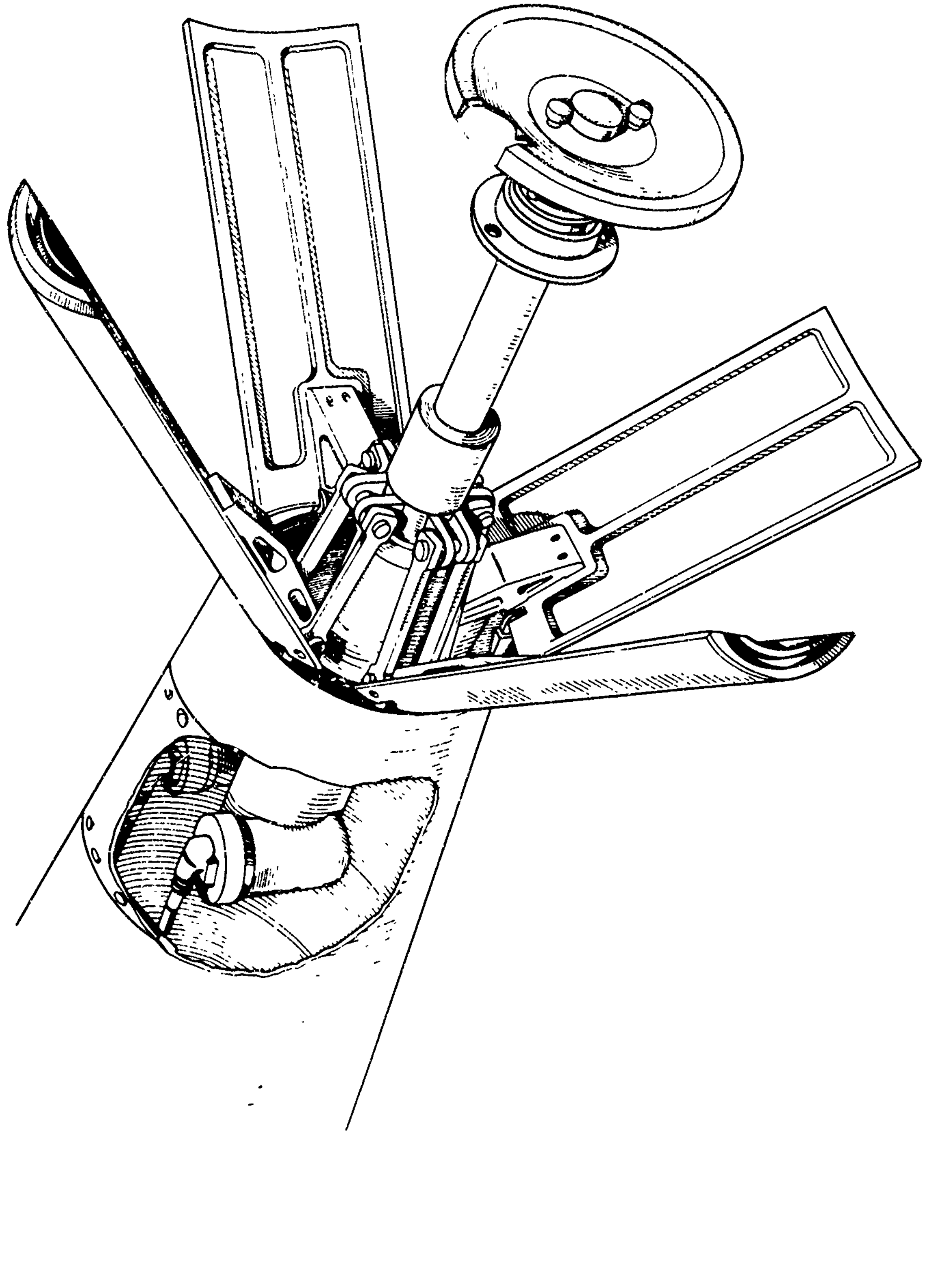


FIG. 20 TYPICAL PNEUMATIC ACTUATION SYSTEM FOR A SPLIT-SKIRT TAIL

CONCLUSIONS

Summarizing the results obtained from the research program on split-skirt stabilizers, the following conclusions have been established.

1. Up to high-subsonic and transonic speeds, the split-skirt does not provide an efficient means of aerodynamic stabilization unless the segments are opened beyond about 15 degrees, at which the center-of-pressure position reaches the body midpoint.

2. Contrary to original expectations, the split-skirt stabilizer with unflanged surfaces is not free from the effects of yaw-induced side forces and moments which can cause catastrophic yaw.

3. With unflanged-skirt segments, roll damping of the stabilizer is critically low so that small asymmetries produce excessive spin rates which readily lead to nonlinear Magnus instability.

4. Satisfactory correlations have been achieved between flight simulation on the computer and the results from range trials.

5. The incorporation of ribs or flanges along the edges of the skirt segments appear to provide an effective means of minimizing the adverse effects of yaw-induced side forces and moments. Furthermore, such flanges substantially increase roll damping and thereby reduce the sensitivity of spin rate to aerodynamic asymmetries.

6. With the adoption of flanged-skirt segments, the concept of a split-skirt stabilizer used to provide a dual mode of high- and low-drag operation appears to be quite feasible. However, a further study would be required to determine realistic estimates of production costs.

7. Correlations between the predicted and observed flight results, based on wind-tunnel measurements and computor studies, have provided considerable insight into problems associated with flight dynamic behavior.

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Table 1

TEST CONDITIONS FOR NAVAL ORDNANCE LABORATORY
SUPERSONIC TUNNEL NO. 1

Mach Number	Dynamic Pressure (lbs/in^2)	Reynolds No/ft x 10^{-6}
0.50	2.10	3.00
0.60	2.80	3.40
0.70	3.48	3.75
0.80	4.13	4.00
0.85	4.42	4.15
0.90	4.70	4.25
0.95	4.90	4.35
1.50	6.13	4.40
1.75	5.80	4.12

TEST CONDITIONS FOR NAVAL SHIP RESEARCH AND DEVELOPMENT
CENTER 7 BY 10-FOOT TRANSONIC TUNNEL

Mach Number	Dynamic Pressure (lbs/in^2)	Reynolds No/ft x 10^{-6}
0.5	2.10	2.90
0.6	2.80	3.20
0.7	3.48	3.65
0.8	4.13	3.95
0.9	4.70	4.20
1.0	5.34	4.45

Table 2

PHYSICAL PROPERTIES, RELEASE CONDITIONS AND IMPACT DEVIATIONS OF INSTRUMENTED BOMB TEST VEHICLES

Round Number			739	740	741
Center of Gravity (percent of body length from nose)			31.0	34.8	36.5
Nominal Split-Skirt Semiangle (degrees)			10	15	12.5
All-up Weight (lb)			939.0	916.5	962.0
Transverse Moment of Inertia (I_y, slug ft^2)			171.3	209.1	263.3
Polar Moment of Inertia (I_x, slug ft^2)			8.8	8.6	9.2
Release Height (ft)			45201	45419	45166
Release Mach Number			0.71	0.71	0.72
Impact Deviation from Particle Trajectory	Range	feet	1116 short	294 short	130 short
		mils	24.7	6.5	2.9
	Line	feet	249 left	51 right	18 left
		mils	5.5	1.1	0.4
	Time	secs	1.42	1.80	0.46

Table 3

FLIGHT CONDITIONS FOR AERODYNAMIC ANALYSIS

Round No.	Skirt Angle (degs)	Time (secs)	Mach No.	Roll Rate (rad/sec)	Incidence Ang. (degs)	Roll (degs)	Reynolds No. x 10^{-6}
739	10	15.739-19.200	0.770-0.832	3.7-4.1	3.0-23.1	116-307	2.3
740	15	6.657-11.016	0.695-0.697	1.9-2.4	7.7-14.7	288-333	1.9

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13 ABSTRACT

Research on the free-fall dynamics of bombs has been conducted as a cooperative program supported by organizations in the United States, United Kingdom and Australia. In addition to full-scale flight trials of instrumented research stores carried out by the Australian Weapons Research Establishment (WRE), wind-tunnel tests have been made on mutually agreed models at the Aircraft Research Association and Royal Aircraft Establishment (RAE) in England; the Naval Ordnance Laboratory (NOL) in the United States; and at the Aeronautical Research Laboratory in Australia. RAE, WRE and NOL have separately prepared digital-computer programs to simulate test vehicle trajectories using wind-tunnel measurements as inputs. Correlation between the predicted and observed flight results have provided considerable insight into problems associated with dynamic behavior during the critical release phase and stability criteria needed for good ballistics consistency.

This is the second report on the research program and it presents results relating to the study of split-skirt stabilizers. These stabilizers are designed to eliminate the effects of roll-yaw cross coupling and to provide a variable-drag capability. Mechanical

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Split-Skirt Stabilizers						
Free-Fall Stores						

ABSTRACT (Cont)

feasibility of an automatically opening two-position split-skirt stabilizers is examined. This report is being issued simultaneously by the Naval Ordnance Laboratory, the Royal Aircraft Establishment and the Weapons Research Establishment.

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